Tenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2013)

Controlled Time of Arrival Feasibility Analysis

David De Smedt
Navigation and CNS Research Unit
EUROCONTROL
Brussels, Belgium
david.de-smedt@eurocontrol.int

Jesper Bronsvoort & Greg McDonald
Air Traffic Control Future Systems
Airservices Australia
Melbourne, Australia
jesper.bronsvoort, greg.mcdonald
@airservicesaustralia.com

Abstract—**Previous research studies and operational trials have shown that using the airborne Required Time of Arrival (RTA) function, an aircraft can individually achieve an assigned time to a metering or merge point accurately. This study goes a step further and investigates the application of RTA to a real sequence of arriving aircraft into Melbourne Australia. Assuming that the actual arrival times were Controlled Time of Arrivals (CTAs) assigned to each aircraft, the study examines if the airborne RTA solution would work. Three scenarios were compared: a baseline scenario being the actual flown trajectories in a two hour time-span into Melbourne, a scenario in which the sequential landing slot times of the baseline scenario were assigned as CTAs and a third scenario in which the landing slots could be freely redistributed to the inbound traffic as CTAs. The research found that pressure on the terminal area would sometimes require aircraft to lose more time than possible through the RTA capability. Using linear holding as an additional measure to absorb extensive delays, up to 500NM (5%) of total track reduction and 1300kg (3%) of total fuel consumption could be saved in the scenario with landing slots freely distributed as CTAs, compared to the baseline scenario. Assigning CTAs in an arrival sequence requires the ground system to have an accurate trajectory predictor to propose additional delay measures (path stretching, linear holding) if necessary. Reducing the achievable time window of the aircraft to add control margin to the RTA function, had a negative impact and increased the amount of intervention other than speed control required to solve the sequence. It was concluded that the RTA capability is not a complete solution but merely a tool to assist in managing the increasing complexity of air traffic.**

Keywords—Required Time of Arrival (RTA); Controlled Time of Arrival (CTA), Trajectory Based Operation; 4D-Trajectory; Arrival Management

I. INTRODUCTION

The pending issue of air traffic growth is clearly recognized by both Europe's Single European Sky Air Traffic Management Research (SESAR) program and the USA's Next Generation Air Transport System (NextGen) program, which aim to reduce the environmental impact of aviation while increasing capacity and safety. A key transformation to achieve these goals is the use of Trajectory Based Operations (TBO), including the use of Controlled Time of Arrival (CTA). The latter might be achieved using the airborne Required Time of Arrival (RTA) functionality, a feature of a modern Flight Management Systems (FMS) designed to calculate and adjust the speed of the aircraft in an attempt to arrive at a point in space at or within a tolerance of a defined target time.

II. BACKGROUND

The SESAR ATM Master Plan states that "Step 1, Time-based Operations, is the building block for the implementation of the SESAR Concept and is focused on flight efficiency, predictability and the environment". It states that "Initial trajectory-based operations are deployed through the use of airborne calculated trajectories (by the ground systems), and a Controlled Time of Arrival (to sequence traffic and manage queues)". Furthermore, according to Step 2 of the Master Plan, "Trajectory-based Operations initiates 4D-based business/mission trajectory management using System Wide Information Management (SWIM) and air/ground trajectory exchange to enable tactical planning and conflict-free route segments" [1].

In parallel, FAA's NextGen Implementation Plan 2012 states that "Enhancements to the navigation capabilities of aircraft, RNAV/RNP with Time of Arrival Control (TOAC) in the descent phase, will begin to increase benefits of trajectory operations through the adaptability of the aircraft trajectory to enable operational predictability and arrival accuracy of aircraft" [2].

A related but alternate approach has been studied in Australia using downlinked information from aircraft as input to improve ground based trajectory prediction. The work by McDonald and Bronsvoort [3] shows that provided aircraft operate in a consistent manner, the ground system can accurately predict the time of arrival at a future point and if adjustment is required, suggest any necessary amended speed. Similarly, a concept of providing aircraft speed advisories to a controller using an advanced ground Trajectory Predictor (TP) and related operational issues were investigated by EUROCONTROL in the TMA2010+ project [4].

Most concepts like those briefly discussed above, emphasize the use of airborne and/or ground TP capability and have one common objective: managing the aircraft's trajectory in order for the aircraft to meet a target time of arrival in a scheduled arrival sequence. The 2015 European Civil Aviation Conference (ECAC) Airspace Concept identifies the metering of traffic in time from en-route into Terminal Airspace along Air Traffic Service (ATS) routes as one of the key enablers to improved traffic management, with RTA being identified as one means to achieve this target [5].

Many studies and operational trials have been undertaken to investigate the performance and behavior of the airborne Required Time of Arrival (RTA) function which enables speed control in the aircraft to meet a Controlled Time of Arrival imposed by Air Traffic Control (ATC) [6] [7] [8] [9]. Those studies indicated that it is technically possible for an aircraft to manage its arrival time with an accuracy of seconds as an order of magnitude. Studies have looked into issues related to the integration of RTA capable aircraft into an operational mixed mode environment [10]. Other studies have identified delivery accuracy improvements which can be gained by moving from a 3D arrival management concept to a 4D concept where arrival time is controlled using the speed adjustments of the RTA function [11] [12]. One study also briefly discussed the effect of the airborne RTA control function on the in-trail separation of two aircraft [12].

The trial "initial-4D" flight of February 2012 operated by Airbus in cooperation with the Maastricht Upper Area Control Centre (MUAC) and the North European and Austrian Consortium (NORACON) demonstrated the future capability of an aircraft downlinking its trajectory and having the ground system coordinate a required time for it to cross at a waypoint. The flight was a successful demonstration of the initial-4D (i4D) technical capability. However it has raised some issues to be addressed, not the least of which was ATC uncertainty of the magnitude in which the aircraft is going to change its speed as it attempts to achieve the RTA [13].

Finally, a paper presented during ATM 2011 by Klooster and De Smedt [14] investigated the probability of a trailing aircraft being able to meet a CTA either 90s or 120s behind the CTA of a leading aircraft, as function of the initial conditions of both aircraft. In addition the paper investigated the probability that either the spacing or the predicted spacing in three minutes time between the two aircraft would reduce below the separation minima. Although the results were technically on the optimistic side, with CTA achievability rates of around 82% and spacing losses below 5%, the paper recommended that additional support tools would be required.

III. PROBLEM DEFINITION

The work performed by Klooster and De Smedt [14] provides a detailed analysis and identification of the scenarios in which a pair of trailing aircraft that are initially separated, and separated by CTAs at a metering fix, would infringe separation standards at some intermediate point while attempting to meet their respective CTAs. While this work is very valuable to help identify possible problem scenarios based on the initial conditions, it does only consider the aircraft pair in question and not the arrival sequence as a whole, with aircraft coming from different directions and merging at different points prior to landing. In addition, the study also assumed a fixed set of initial conditions for the aircraft pairs. For example, the initial spacing between one pair was assumed to be between 10 and 20NM at an altitude between FL310 and FL390 and at a distance between 170 and 230NM from the CTA waypoint.

Similarly, in terms of previous performed studies and flight trials, only a few aircraft would usually simultaneously make use of CTA, while all other aircraft were treated the traditional way by ATC. Little work is being performed on assessing the use of CTA to solve a complete sequence of arriving aircraft in a realistic traffic scenario.

In contrast of earlier studies, the research presented in this paper has taken a true busy traffic scenario at Melbourne Australia and investigated how CTA could have been used to handle the same flow of inbound traffic as controllers actually handled with use of conventional tactical clearances. The CTA operation was assumed to start before the Top of Descent of the aircraft, at a 200NM sequence horizon from the airport. The research aims to find an answer to the following questions:

- Does the assumed 200NM sequence horizon provide enough control authority for the FMS to use the RTA function to meet CTAs set by the arrival manager on the ground?
- In addition, what is the impact of airborne RTA control on legacy arrival manager systems on the ground?
- Is the traditional "first-come-first-served" methodology applied by many legacy arrival managers like the one deployed at Melbourne too conservative for a concept involving airborne RTA functionality?
- In resolving the sequence, how many conflicts do occur?
- In general, can the application of CTA successfully resolve a sequence for an actual traffic scenario without the controllers having to revert to conventional sequencing techniques?

IV. SIMULATION ENVIRONMENT AND SETUP

In order to provide answers to the questions above, the complete Melbourne Terminal Area (TMA) and en-route airspace structure up to a distance of 200NM from the airport was modeled in a fast time simulation environment. A custom EUROCONTROL fast time simulation model was used to produce an arrival flow into Melbourne airport using a real traffic data sample and historical meteorological data as input.

The aircraft types as well as the initial positions (latitude and longitude), flight levels and UTC times of each aircraft at a 200NM direct distance from Melbourne airport were extracted from the recorded Melbourne arriving traffic sample and used as initial conditions in the fast time simulator. Wind direction, wind speed and temperature at 10 different altitudes were extracted from historical data and inserted for each arriving aircraft in the fast time simulator.

Aircraft performance was modeled in the simulator using aerodynamic data from the BADA (version 3.7) aircraft performance model (APM) [15]. The vertical profiles generated by the trajectory predictor used in the simulation model were based on the following equation [16]:

$$mg \cdot \sin(\gamma) = T - D + m\left(\frac{d(TAS)}{dt} + \frac{dW}{dt}\right). \quad (1)$$

Where:

m	point mass representing aircraft (kg),
g	acceleration of gravity = 9.81m/s^2,
γ	aerodynamic flight path angle (small),
T	thrust (N),
D	drag (N),
TAS	true airspeed (m/s),
t	time (s),
W	horizontal wind component (m/s).

The vertical profiles for turboprop aircraft were modeled using a fixed vertical rate of 1500 feet per minute above FL100 and 1000 feet per minute below FL100.

The fast time simulator computes the aircraft's lateral position assuming that the aircraft flies a loxodromic route, maintaining a constant true track on straight segments. Turns are modeled assuming that the aircraft maintains a constant bank angle during the turn, which is defined by the track change Δtrack as follows:

$$\text{Bank} = \text{Min}\left[5, \text{Max}\left(30, \frac{\Delta\text{track}}{2}\right)\right]. \quad (2)$$

Aircraft decelerations were computed using an energy share factor during the descent phase of flight [15]. A speed limitation of 250 Knots Indicated Air Speed (KIAS) below FL100 was taken into account for the computation of the speed profile. The final approach of each aircraft was modeled as a fixed 3 degree geometric profile between threshold elevation and 3000ft. The approach speed was kept constant at 140KIAS for jet aircraft and 120KIAS for turboprop aircraft between threshold elevation and 1000ft. Decelerations during final approach were computed assuming a constant True Airspeed deceleration rate of 0.4 knots/s from glide path interception at 3000ft until final approach stabilization at 1000ft.

As the fast-time simulations for the research undertaken for this paper required very accurate aircraft speed envelopes, the latter were modeled using data from aircraft performance manuals and flight crew operating manuals in order to represent the most realistic operating ranges [17] [18] [19] [20]. The maximum operating speed and Mach number (V_{MO} and M_{MO}) were further limited using a corrected V_{MO}/M_{MO} to take into account additional limitations on the maximum speeds imposed by the aircraft's FMS. An example of the minimum and maximum Mach numbers and Calibrated Air Speeds (CAS) is provided in Table I, for two different altitudes and for four different aircraft types. To reduce the number of parameters in the simulations, the aircraft weight was assumed to be 90% of the Maximum Landing Weight (MLW) for a particular aircraft type.

The EUROCONTROL fast-time simulation model used for this research has the capability of calculating a required speed profile (Mach/CAS combination) to meet a given CTA at a defined waypoint. This is done using a "quick sort algorithm"

TABLE I. EXAMPLE OF AIRCRAFT SPEED ENVELOPES USED

	B737	**A320**	**A333**	**B77W**
Weight (kg)	52250	58050	166500	226160
Min. CAS FL300 (kts)	204	206	217	250
Min. CAS FL350 (kts)	206	211	222	253
V_{MO} (kts) / M_{MO}	340 / 0.82	350 / 0.82	330 / 0.86	330 / 0.89
Corrected V_{MO} (kts) / M_{MO}	330 / 0.80	340 / 0.80	315 / 0.83	315 / 0.86

which iterates the speed profile within the speed envelope of the aircraft until the computed Estimate Time of Arrival (ETA) matches the CTA within a defined tolerance. This methodology is described in detail in [21] and [22]. In addition, the model also computes the earliest and latest achievable arrival times, also called $ETA_{min} - ETA_{max}$ times.

In this study CTAs were set at the runway threshold rather than a mid-descent metering fix as to simulate a situation in which no further ATC intervention would be required after passing the metering fix to meet a required landing slot time.

The fast-time simulation model performed a series of simulations to evaluate and compare the following three scenarios:

- **Baseline scenario**: this scenario consists of the actual arrival flows into Melbourne airport starting from a 200NM radius around the airport, recorded by Airservices Australia during a 2 hour medium to high density operation.
- **CTA scenario**: this scenario uses identical initial conditions as the baseline scenario with the objective to meet the landing times of the baseline scenario by means of speed control while keeping the aircraft on its flight planned route.
- **CTA + modified sequence scenario**: this scenario is identical as the previous scenario except that the runway landing slots of the baseline scenario may be freely allocated to the arriving aircraft if this leads to an improved sequence.

Note that in the third scenario, although the order of arriving aircraft may be changed to improve the sequence, it was decided to maintain the absolute value of the landing times and thus the subsequent landing interval times. This was done to not interfere with departing aircraft, which in the simulation could maintain their slot in the overall runway sequence.

V. DATA SAMPLE AND AIRSPACE DESCRIPTION

Real traffic data was sourced from Melbourne Australia. Melbourne airport has a fairly typical architecture with two runways, one oriented North-South (34/16) and the other, a crossing runway, oriented East-West (27/09). Traffic is arranged so that there is a basic segregated and separated Terminal Area flight path structure with arriving traffic coming through one of a number of Feeder Fix Metering Points at approximately 30-40 miles from the destination. The segregated and separated flight paths within the Terminal Area are based on published procedures linking the planned route at the Feeder Fix to the landing runway. The normal traffic handling procedures at Melbourne use time based sequencing to each Feeder Fix managed by an arrival manager, Maestro. The arrival manager arranges a sequence at the destination according to agreed acceptance rates and using tables to calculate the time each aircraft must cross its specific Feeder Fix. Fig. 1 provides an illustration of the structure around Melbourne and routes from the feeder fixes ARBEY, BOYSE, LIZZY, BADGR, WAREN, PORTS and WENDY.

In the current situation, the air traffic controller adjusts the profile of the arriving aircraft to achieve the sequence time at the Feeder Fix (within a time interval of plus or minus one minute) by a range of methods, including speed instructions, radar vectors and sometimes holding. Assigning a lower cruise level is generally not employed as the amount of delay it would cause is an unknown quantity and difficult to estimate.

On days with light winds, Melbourne airport operates using more than one arrival runway. While this method of operation increases the landing rate, for simplification it was decided to extract a data sample during a time interval with one runway in use. Melbourne also has a significant amount of turboprop aircraft, which were included in the selected data sample.

Fig. 2 indicates the number of operations per hour, respectively for arrivals, departures and both, recorded in Melbourne on the 8th of August 2012. Note that the times in the figure are indicated in Coordinated Universal Time (UTC) and local time in Melbourne for this period is UTC + 10 hours. On this day, strong Northerly winds predicated the use of a single runway, being RWY34. As the strong winds and single runway operation had been forecast to occur, the arrival rate had been set the previous evening and airlines had scheduled to meet that rate. The rate does include a certain factor of "pressure" on the TMA to ensure the desired landing rate is maintained as evidenced by the sequencing actions applied by ATC. Two peaks can be observed in the figure: one occurring in the morning (from 22:00 UTC on the previous day until 02:00 UTC) and another one in the evening around 10:00 UTC. Taking into account the quality of the data, it was decided to retain the data around the second (evening) peak, from 09:00 UTC until 11:00 UTC and use this sample as input for the three scenarios defined above in Section IV.

Flight data processing records were extracted for the chosen period to determine the true landing sequence and from that list the relevant radar tracks were matched, filtered to within a radius of 200NM from the destination. The distance of 200NM was chosen because most aircraft are still cruising at this distance and it was assumed that there is a reasonable amount of remaining time to affect sequencing actions.

Fig. 3 illustrates the runway slot intervals during the selected period. The red and green triangles indicate whether an operation on the runway at a given time is a departure or an arrival. The elapsed time since the previous operation on the runway can be read from the vertical axis. It can be seen that departures are usually alternating with arrivals, usually with shorter intervals between a departure and a subsequent arrival. The first 45 minutes of the two hour period is the busiest, with runway intervals of around 1 minute. Thereafter runway pressure reduces slightly. The line in grey in the chart illustrates the elapsed time on the runway between two landings, which is on the average around 2.5 minutes.

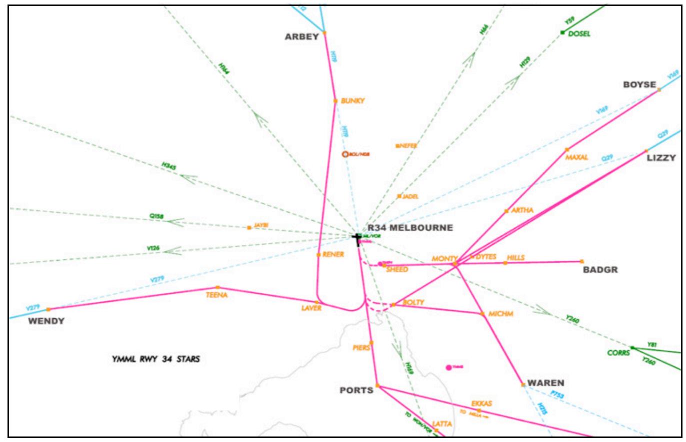

Figure 1. STAR tracking for RWY34 Melbourne airport (YMML).

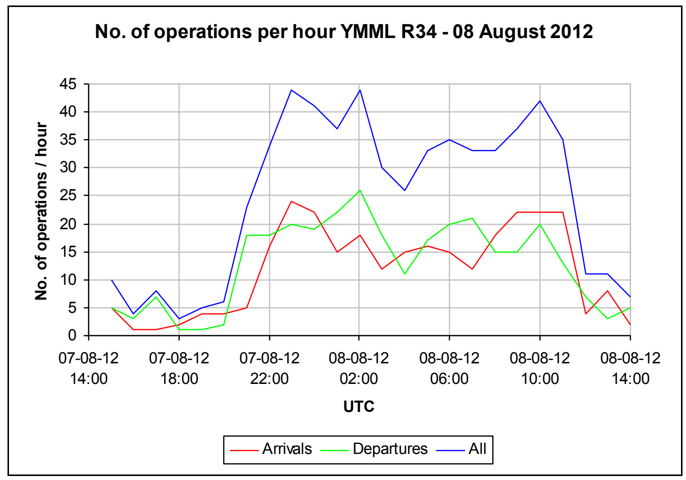

Figure 2. Number of operations per hour using RWY34 on 8th of Aug. 2012.

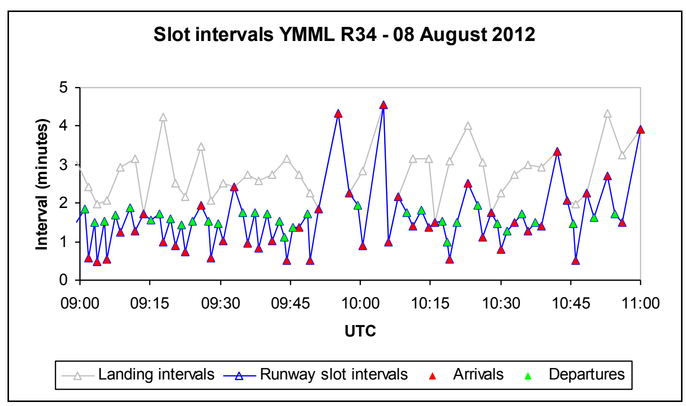

Figure 3. Slot intervals using RWY34 in YMML on 8th of Aug. 2012.

VI. Simulation Results

A. *Baseline scenario*

Fig. 4 and 7 provide an overview of the lateral and vertical components of the actual trajectories flown during the first hour of the selected two hour data sample recorded between 09 and 11 hours UTC on the 8th of August 2012 in Melbourne.

Aircraft arrival flows can be observed coming in via the five Feeder Fixes, ARBEY, LIZZY, BADGR, WAREN, and WENDY, which are shown on the chart in Fig. 1.

The sequence of runway slot intervals illustrated in Fig. 3 already indicated that the first 45 minutes of the two hour data sample had the greatest demand and this can again be observed in Fig. 4, which shows a lot of tactical control through path extensions to achieve delay. Despite lots of lateral tactical control, the descent profiles illustrated in Fig. 7 indicate that descents were usually continuous, often approximating a near idle descent. Australia has an integrated enroute and TMA system which simplifies hand-off agreements and reduces the need for standard processing of aircraft across the TMA boundary often resulting in level segments flown.

Fig. 10 and 13 illustrate the lateral and vertical components of the trajectories flown during the second hour of the data sample. As analyzed in Fig. 3, traffic density was slightly lower compared to the first hour. This can also be observed in the trajectory plots by the lower amount of tactical measures.

The total two hour traffic sample contained a mixture of single aisle and wide-body Airbus and Boeing aircraft types, one Embraer E190 and two turboprops (call signs "RXA3683", a Saab SF34 and "TFX152", a Metroliner SW4).

B. Controlled Time of Arrival (CTA) scenario

Fig. 5 and 8 provide the results of the first CTA scenario simulation performed. In this scenario the objective was to maintain the sequence and landing times as in the baseline scenario by means of speed control solely, while keeping the aircraft as much as possible on the lateral route. For each aircraft, the recorded landing time of the baseline scenario was inserted as a CTA at the landing threshold. Thereafter a required speed profile to meet this CTA was calculated using the EUROCONTROL fast-time simulator. Minimum and maximum speeds were the real minimum and maximum speeds of the aircraft as illustrated in Table I.

A first interesting observation is that all aircraft in the CTA scenario needed to reduce speed. For nine aircraft out of the total sample of 23 aircraft arriving during the first hour, it was impossible to provide enough speed reduction to meet the CTA without reducing speed below the minimum speed (see also Table II). Therefore, the speed was reduced to the minimum speed and in addition the aircraft was descended to a lower cruise level where a lower True Airspeed (TAS) could be flown. This technique, called "linear holding" is an efficient way of imposing delay and was already discussed in [23]. In addition, the Airbus document "Getting to grips with fuel economy" [24] provides a table indicating for different aircraft types the most optimal altitude band for linear holding at reduced speed (green dot speed). It seems that on the average, for most aircraft types displayed in the table, this altitude band is around FL200-FL250. Note that some intermediate level-offs can also be observed at 9000ft in the vertical plots. This is due to a procedural altitude constraint in the arrival route via ARBEY, which the simulator accounted for.

The reason why in the CTA scenario, speed reduction alone was often not enough to match the arrival times of the baseline scenario, is obviously due to excessive delays being issued to some aircraft as evidenced by the extensive path stretching in the baseline scenario. In addition, it was observed that some aircraft in the baseline scenario were already cruising at quite a reduced speed. This was probably due to a speed instruction imposed by ATC in an attempt to impose delay, in combination with the radar vectoring. For one aircraft operating with call sign "MAS129", reducing speed in combination with a step descent to a lower altitude was even not enough to match the CTA. For this aircraft a path extension, although less extensive than in the baseline scenario was applied in addition.

It is obvious that the trajectories in the baseline scenario were conflict-free, as the real situation was recorded in Melbourne at a peak time, when ATC actively separated the aircraft. The arrival trajectories of the simulated CTA scenario were compared with each other to investigate if there were any conflicts in this scenario. This was based on the computation of the great circle distance between the latitudinal/longitudinal positions and the vertical spacing of each aircraft pair, time-coincidental. A separation infringement was identified whenever the 5NM and 1000ft separation standards were breached during cruise and initial descent phase of flight, and whenever the 3NM and 1000ft separation standards were breached within 30NM of the airport. In total, 5 separation infringements were found, all on the arrival route via LIZZI. Those are displayed by the colored dots in Fig. 5 and 8.

Fig. 11 and 14 provide the simulation output of the CTA scenario for the second hour in the two hour traffic sample. Even though traffic density is less intense, which is visible in the results, three aircraft were unable to meet the CTA with speed control only and needed to absorb a significant amount of delay at an intermediate altitude. For one aircraft ("RBA53", a B772), a path extension was required in addition. No conflicts were identified during this hour.

C. Controlled Time of Arrival (CTA) with modified sequence scenario

Results of the third scenario are plotted in Fig. 6 and 9 for the first hour and Fig. 12 and 15 for the second hour of the traffic sample. In this scenario, the arrival sequence was modified by re-assigning the original set of CTAs to the arriving aircraft in order to respect more optimally each aircraft's desired ETA and to reduce the number of CTAs that fall outside the ETA_{min} – ETA_{max} window of an aircraft (defined in Section VII). This improved the situation significantly (see Table II) and most importantly, there were no longer any separation infringements between arriving aircraft in this scenario. The amount of extensive linear holding at intermediate flight levels was reduced from nine to five during the first hour and from three to zero during the second hour of the sample. In addition, the average duration of the linear holding was significantly reduced indicating that the original sequence was not efficient, possibly due to inaccurate trajectory prediction by the arrival manager. Note that changing the order between VOZ342 and QFA694 in the modified sequence caused both aircraft not to meet the CTA instead of only QFA694, but the total deviation from the CTA was less (63 + 36 sec combined instead of a single 170 sec, see Table II).

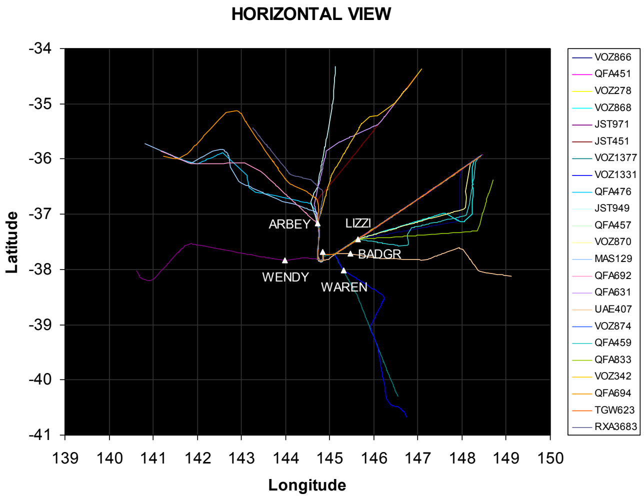

Figure 4. YMML arrivals 09-10 UTC – Baseline.

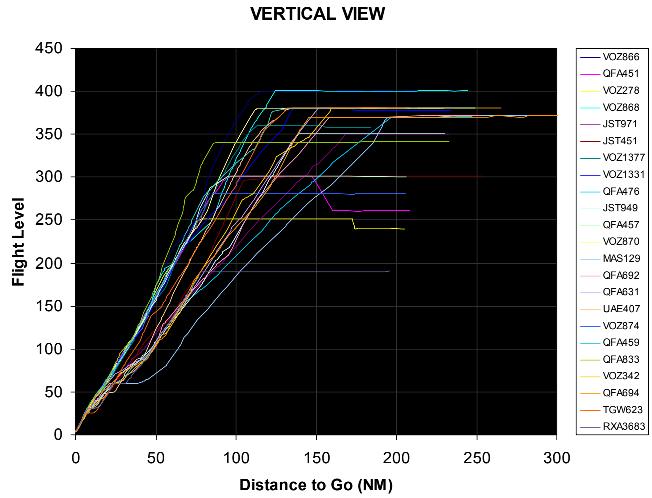

Figure 7. YMML arrivals 09-10 UTC – Baseline.

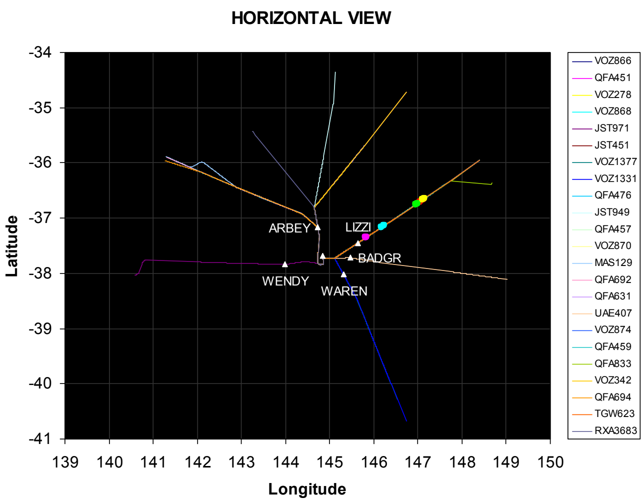

Figure 5. YMML arrivals 09-10 UTC – CTA scenario.

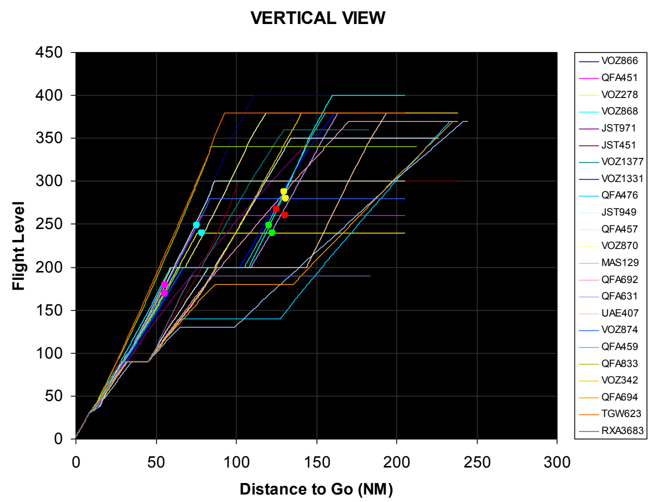

Figure 8. YMML arrivals 09-10 UTC – CTA scenario.

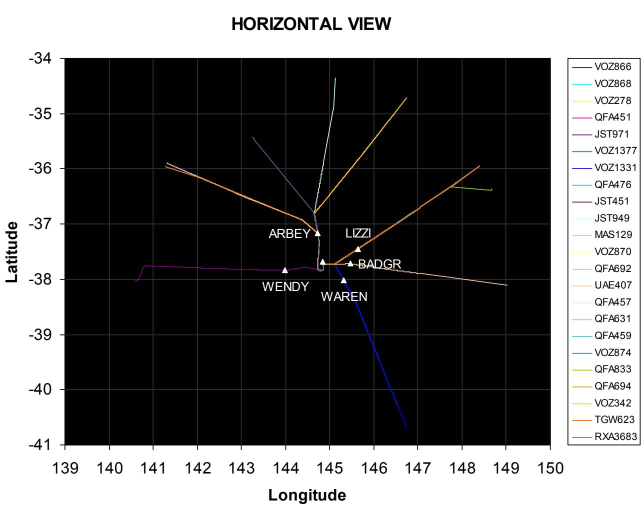

Figure 6. YMML arrivals 09-10 UTC – CTA + modified sequence.

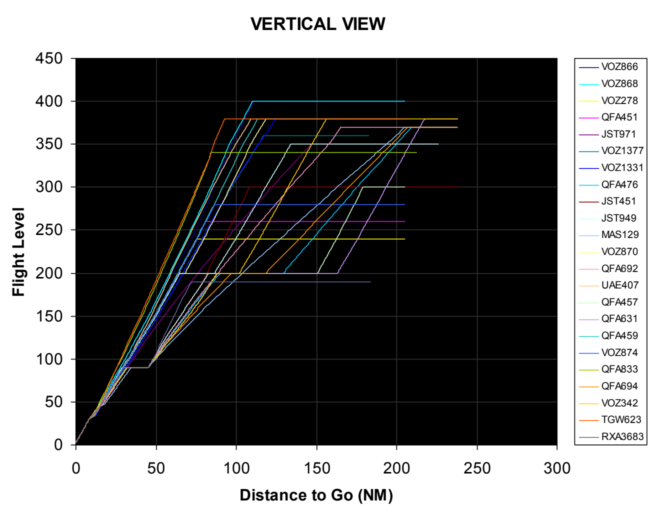

Figure 9. YMML arrivals 09-10 UTC – CTA + modified sequence.

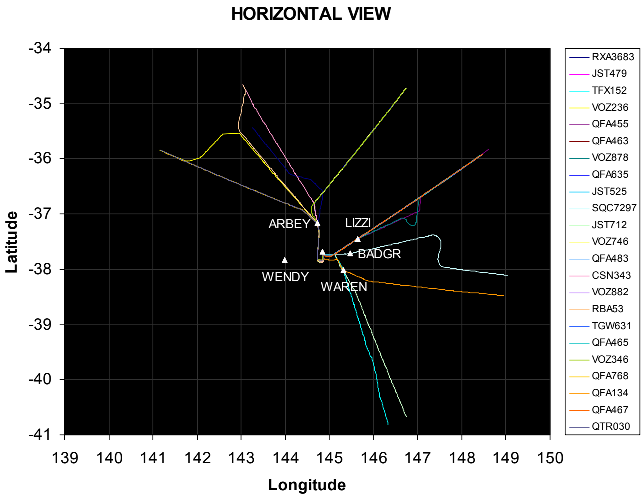

Figure 10. YMML arrivals 10-11 UTC – Baseline.

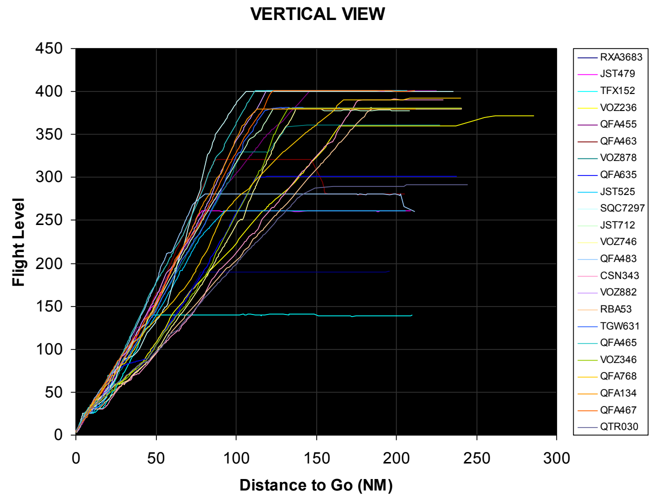

Figure 13. YMML arrivals 10-11 UTC – Baseline.

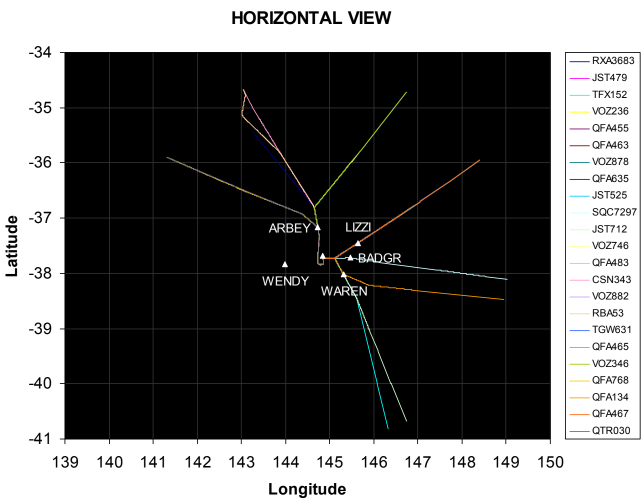

Figure 11. YMML arrivals 10-11 UTC – CTA scenario.

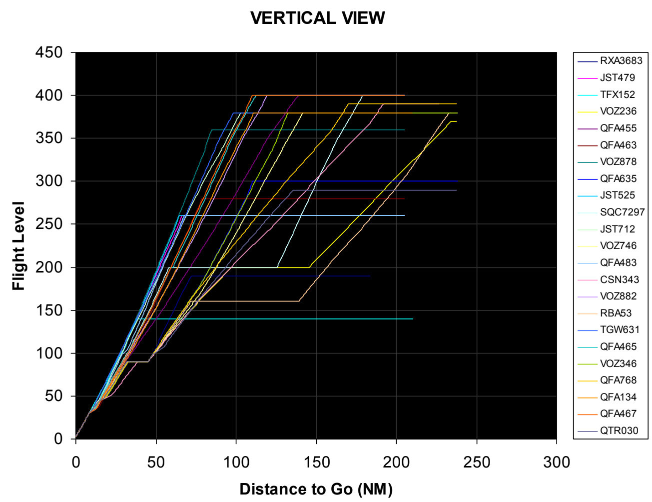

Figure 14. YMML arrivals 10-11 UTC – CTA scenario.

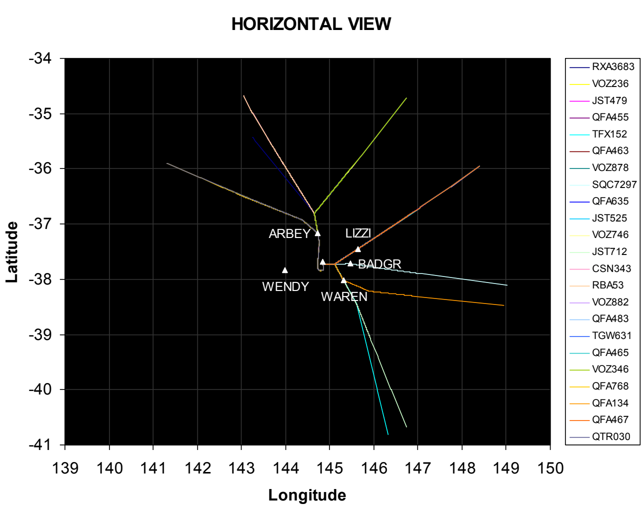

Figure 12. YMML arrivals 10-11 UTC – CTA + modified sequence.

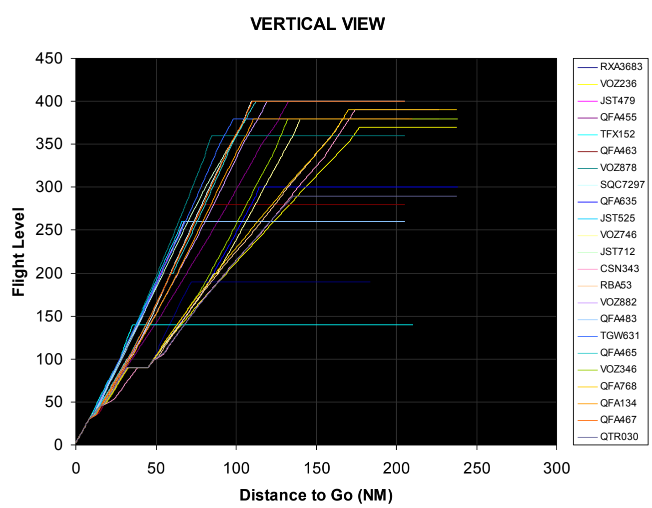

Figure 15. YMML arrivals 10-11 UTC – CTA + modified sequence.

VII. Quantification of Simulation Results

EUROCAE Working Groups 78 and 85 in concert with RTCA Special Committees 214 and 227 have been tasked with creating the standards necessary for RTA and initial-4D navigation. Initial-4D involves the aircraft downlinking trajectory information, also called Extended Predicted Profile (EPP). The downlinked information can also contain the earliest and latest possible time for waypoints in the trajectory. The idea being that the ground system can then assign a time to the aircraft and know that the time is within an achievable range. A proposal from aircraft manufacturers is to only downlink a reduced achievable time-window (also called "reliable" ETA_{min} – ETA_{max} window) rather than the full window, which would result in a greater certainty of the aircraft actually achieving the required time [25].

Because of the difficulty in matching the CTAs within the real ETA_{min} – ETA_{max} windows in the simulation scenarios discussed in section VI, the CTA scenario was repeated to investigate what would be the effect if the ETA_{min} – ETA_{max} window was further reduced. Therefore, a "reliable" ETA_{min} – ETA_{max} was calculated using the maximum Calibrated Airspeed (CAS) minus 20 Knots (and an equivalent in Mach) to determine ETA_{min} and the maximum value of the current minimum CAS and the minimum CAS at target altitude (end of descent point) plus 20 Knots to determine ETA_{max}.

Table II provides a quantitative overview of the results, showing the list of CTAs equaling the landing times of the baseline scenario (first column), the results of the extra simulation using a reliable ETA_{min} – ETA_{max} window (second column), the results of the CTA scenario using the real ETA_{min} – ETA_{max} window (third column) and finally the results of the CTA with modified sequence scenario using the real ETA_{min} – ETA_{max} window (fourth column). For each simulation result, the following information is provided: the sequence of call signs to which the CTAs were assigned, a label indicating whether the CTAs were achievable or not (green for achievable and red for unachievable) as well as two parameters labeled "Dev" and "X". Dev represents the additional amount of time that needs to be lost after the application of a maximum speed reduction or in other words, the CTA minus the ETA_{max}. X represents the position of the CTA within the ETA_{min} – ETA_{max} window. X is defined as zero if the CTA coincides with the ETA_{min}, 0.5 if the CTA is nicely in the middle of the window and 1 or larger than 1 if the CTA is equal to or larger than the ETA_{max}. Mathematically this can be expressed as follows:

$$\mathrm{Dev} = \mathrm{Max}(0, \mathrm{CTA} - \mathrm{ETA}_{max}), \tag{3}$$

$$X = \frac{\mathrm{CTA} - \mathrm{ETA}_{min}}{\mathrm{ETA}_{max} - \mathrm{ETA}_{min}}. \tag{4}$$

TABLE II. YMML Arrivals 09-11 UTC – CTA scenarios with reliable versus real ETA windows and CTA scenario with modified sequence

CTA	CTA scenario (reliable ETAmin-max)					CTA scenario (real ETAmin-max)				CTA + modified sequence (real ETAmin-max)			
	Call sign	Type	CTA possible	Dev	X	Call sign	CTA possible	Dev	X	Call sign	CTA possible	Dev	X
08:59:42	VOZ866	B737		00:02:21	1.29	VOZ866		00:00:08	1.01	VOZ866		00:00:08	1.01
09:01:59	QFA451	B738			0.80	QFA451			0.63	VOZ868			0.95
09:04:11	VOZ278	B738		00:01:33	1.12	VOZ278			0.84	VOZ278			0.84
09:06:14	VOZ868	B737		00:05:55	1.74	VOZ868		00:03:42	1.33	QFA451			0.87
09:08:49	JST971	A320		00:01:24	1.25	JST971			0.98	JST971			0.98
09:12:13	JST451	A320			0.50	JST451			0.44	VOZ1377			0.87
09:14:14	VOZ1377	B738		00:02:51	1.41	VOZ1377		00:00:43	1.07	VOZ1331			0.88
09:17:57	VOZ1331	B738		00:04:35	1.65	VOZ1331		00:02:30	1.25	QFA476		00:01:56	1.25
09:20:47	QFA476	B763		00:06:11	2.07	QFA476		00:04:46	1.61	JST451			0.96
09:22:48	JST949	A320		00:02:23	1.32	JST949		00:00:08	1.01	JST949		00:00:08	1.01
09:26:28	QFA457	B738			0.68	QFA457			0.56	MAS129			0.86
09:28:14	VOZ870	B738		00:02:29	1.33	VOZ870		00:00:10	1.02	VOZ870		00:00:10	1.02
09:30:56	MAS129	A333		00:05:18	2.15	MAS129		00:03:27	1.47	QFA692			0.73
09:33:03	QFA692	B763		00:01:26	1.25	QFA692			1.00	UAE407			0.94
09:35:43	QFA631	B738		00:03:20	1.44	QFA631		00:01:04	1.10	QFA457		00:02:19	1.15
09:38:26	UAE407	B77W		00:05:42	3.22	UAE407		00:05:08	2.19	QFA631		00:03:47	1.35
09:41:04	VOZ874	B738			0.86	VOZ874			0.68	QFA459			0.89
09:44:39	QFA459	B738		00:04:40	1.61	QFA459		00:02:24	1.22	VOZ874			0.89
09:47:11	QFA833	B734		00:01:02	1.10	QFA833			0.91	QFA833			0.91
09:49:33	VOZ342	B738		00:01:11	1.16	VOZ342			0.89	QFA694		00:01:03	1.13
09:51:20	QFA694	B738		00:04:43	1.84	QFA694		00:02:50	1.35	VOZ342		00:00:36	1.06
09:55:29	TGW623	A320			0.62	TGW623			0.54	TGW623			0.54
09:57:46	RXA3683	SF34			0.97	RXA3683			0.70	RXA3683			0.70
10:00:42	JST479	A320			0.71	JST479			0.58	VOZ236			0.75
10:03:49	TFX152	SW4			0.84	TFX152			0.58	JST479			0.74
10:05:07	VOZ236	B738		00:04:16	1.76	VOZ236		00:02:24	1.30	QFA455			0.63
10:08:30	QFA455	A333		00:02:04	1.36	QFA455		00:00:03	1.01	TFX152			0.75
10:11:33	QFA463	B763			0.51	QFA463			0.45	QFA463			0.45
10:14:29	VOZ878	E190			0.77	VOZ878			0.63	VOZ878			0.63
10:16:08	QFA635	B738			0.65	QFA635			0.54	SQC7297			0.65
10:19:14	JST525	A320			0.41	JST525			0.37	QFA635			0.74
10:23:12	SQC7297	B744		00:05:29	2.09	SQC7297		00:04:49	1.76	JST525			0.57
10:26:08	JST712	A320			0.72	JST712			0.61	VOZ746			0.77
10:28:00	VOZ746	B738		00:01:41	1.22	VOZ746			0.95	JST712			0.80
10:30:16	QFA483	B734			0.36	QFA483			0.34	CSN343			0.30
10:33:09	CSN343	A332			0.81	CSN343			0.65	RBA53			0.75
10:36:16	VOZ882	B738		00:00:36	1.09	VOZ882			0.85	VOZ882			0.85
10:38:47	RBA53	B772		00:05:18	4.07	RBA53		00:04:55	2.73	QFA483			0.79
10:42:06	TGW631	A320		00:01:43	1.22	TGW631			0.97	TGW631			0.97
10:44:19	QFA465	B763		00:01:33	1.20	QFA465		00:00:05	1.01	QFA465		00:00:05	1.01
10:46:22	VOZ346	B738			0.66	VOZ346			0.55	VOZ346			0.55
10:48:30	QFA768	B763			0.68	QFA768			0.59	QFA768			0.59
10:53:00	QFA134	B738			0.99	QFA134			0.78	QFA134			0.78
10:56:03	QFA467	B763			0.86	QFA467			0.74	QFA467			0.74
11:00:04	QTR030	B77L			0.25	QTR030			0.39	QTR030			0.39
SUM				**01:19:45**				**00:39:16**				**00:10:12**	
AVG					**1.21**				**0.94**				**0.82**
STD					**0.71**				**0.48**				**0.21**

Conflicts were evaluated for the simulations using the real ETA_{min} – ETA_{max} windows and are indicated by means of crosses in the CTA achievable/unachievable labels. Call signs for which the position in the sequence was changed in the CTA with modified sequence scenario are highlighted in color. It can be observed that the width of the ETA_{min} – ETA_{max} window has a significant influence on the amount of CTAs that are achievable and also on the total extra time that needs to be lost, which is calculated for each scenario in the bottom row. The bottom row of the table also displays the average of X as well as the standard deviation for each scenario. It can be seen that obviously, a wider ETA window and a good organization of the arrival sequence has a positive impact on the average position of the CTA within the achievable ETA window.

Finally, Table III represents the overall performance indicators of the baseline scenario, compared with the CTA with modified sequence scenario. The performance indicators are expressed as total distance flown, total distance flown during cruise operation, distance flown during intermediate level-offs (excluding procedural like the 9000ft at BUNKY) and total fuel consumption. The results are presented hourly for the two hour traffic sample as well as for the total sample. The fuel consumptions were computed using the thrust specific fuel consumption (TSFC) calculations for cruise and empirical formulas for idle descents provided by the BADA model [15]. It should be noted that the fuel figures for the baseline scenario are probably underestimated as not all of the descents were idle in this scenario. The improvements in terms of total reduction in track miles flown and total fuel consumed are more modest for the second hour of the traffic sample, which indicates that the performance of the baseline scenario was already good. Overall reduction in total distance flown and total fuel consumed was in the order of magnitude of respectively 500NM (5%) and 1300kg (3%), for the complete 2 hour sample consisting of 45 arriving aircraft. Note that as mentioned, the fuel consumption reduction might be underestimated though.

VIII. OPERATIONAL IMPLICATION OF RESULTS

The results presented in this paper provide indication that a CTA application consisting solely of airborne RTA based speed control, is unlikely to be sufficient to solve a sequence of arriving aircraft in a medium to heavy traffic scenario. While the investigated scenario for Melbourne was busy, it is likely that certain airports in the US and Europe are under more pressure suggesting even less satisfactory results.

Answering the research questions raised in Section III, the results indicate that a horizon of 200NM does not provide enough control authority for the FMS to meet the CTA with speed control only. Ideally this horizon should be extended, however that might raise other complexities in terms of coordination between different ATC centers and therefore raises the need for wider information sharing.

Moving away from the "first-come, first-serve" logic of legacy arrival managers improved the situation but even then the investigated scenario could not be resolved by speed control alone. For the modified sequence (not "first-come, first-serve") according to Table II, the average position of the RTA in the ETA_{min} – ETA_{max} window was still 0.82 with a standard deviation of 0.21, which still results in a very critical sequence. Only during the second hour of the modified sequence, the demand had reduced to a level such that all aircraft (except for QFA465 with only 5 seconds deviation) were able to be assigned a slot within their ETA_{min} – ETA_{max} window.

The results indicate that when the demand on the airport increases, the concept of an arrival manager on the ground that shuffles the arriving aircraft into a sequence based on their downlinked ETA_{min} – ETA_{max} window, is likely not to find a solution as the accumulating delay for an aircraft further up in the sequence exceeds the airborne RTA control range capability as limited by the ETA_{max}. Therefore with a fixed CTA horizon, such high demand scenarios will require a combined air and ground approach to provide a sequence resolution. For example some "pre-conditioning" of the traffic might be required to lower the average relative position of the CTA within the ETA_{min} – ETA_{max} window, which might be accomplished through for example cruise speed control well outside the 200NM CTA horizon.

If pre-conditioning is not possible, a combined approach is required within the 200NM horizon. In this study, level changes were used to absorb the additional delay. However this is not something an FMS currently can determine without manual pilot input. Another option is to combine speed control with (cruise) path stretching. While absorbing delay through cruise path stretching is not as efficient as assigning a lower cruise level, the former might be easier to implement. An example of this strategy is the Speed And Route Advisor (SARA), which is being trialed at Amsterdam Schiphol [26]. As the calculation of both level change and path stretches to achieve delays are beyond the current capability of the FMS, the combined approaches call for accurate trajectory prediction capability to be available on the ground as to assist in such sequence resolution advisories.

In summary and in reference to the last research question, the results show that CTA solves some of the sequence problems but when the arrival demand exceeds some point, controllers will need to revert to conventional techniques to make all aircraft fit in the absence of ground based support. Question is, in a mixed mode environment, how much of the benefit gained by the RTA capable aircraft is cancelled against other aircraft that would have been delayed using traditional ATC methods of holding and low level radar vectoring.

TABLE III. OVERALL PERFORMANCE INDICATORS OF BASELINE VERSUS CTA + MODIFIED SEQUENCE SCENARIOS

Scenario	Total Distance (NM)	Cruise (NM)	Level Offs (NM)	Total Fuel Consumption (kg)
Baseline 09-10 UTC	5317	2548	0	20816
Baseline 10-11 UTC	4885	2174	0	23390
Baseline Total	**10202**	**4723**	**0**	**44206**
CTA + modified sequence 09-10 UTC	4952	1951	245	19793
CTA + modified sequence 10-11 UTC	4766	2274	0	23096
CTA + modified sequence Total	**9718**	**4225**	**245**	**42889**

IX. CONCLUSIONS AND FURTHER WORK

The conclusions from this work add complexity to the CTA premise and its airborne RTA solution, on which much of SESAR and NextGen are based. This paper has shown that assigning CTAs to a sequence of aircraft and using the RTA function to comply, is on average more fuel efficient than traditional ATC sequencing. However for dense traffic scenarios, the required delay cannot be achieved using solely RTA. The simulation was able to find a solution to absorb the additional delay, such as the early descents, which in reality would have flagged an "unachievable RTA" to the flight crew.

High density traffic situations for which RTA control does not deliver acceptable results, require sequence resolutions generated external to the FMS, e.g. path stretches or level changes. Therefore accurate ground based trajectory prediction is required, and only in the case where an arrival manager is able to shuffle all aircraft into a sequence based on downlinked achievable time windows, a solely airborne solution could be sufficient. In the simulations, this was only shown possible for the lower density traffic sample, with reduced benefits.

Often the CTA was well outside of the achievable time window. Current proposals to reduce the achievable window to incorporate a control margin for the RTA function would exacerbate the problem. Increasing the CTA horizon beyond 200NM would increase the achievable window although this would create coordination difficulties and requires wider information sharing. Coupled with the critical assumption of this research that all aircraft in the sequence were capable of achieving the assigned RTA accurately, this indicates that there is a significant amount of work yet to be done to have a smoothly operating time-based ATM system in all traffic scenarios. In turn this raises the point that RTA control is perhaps not the total solution but merely one element in the toolset of traffic managers to efficiently process the increasing amount of air traffic.

REFERENCES

[1] "European ATM Master Plan Edition 2," SESAR Consortium, October 2012.

[2] "NextGen Implementation Plan Edition March 2012," Federal Aviation Adminstration, Washington, D.C., March 2012.

[3] G. McDonald, J. Bronsvoort, "Concept of Operations for Air Traffic Management by Managing Uncertainty through Multiple Metering Points," Air Transport and Operations Symposium 2012, Delft, The Netherlands, June 2012.

[4] "TMA2010+ Project North RTS2 Simulation Report," EUROCONTROL, June 2009.

[5] "The 2015 Airspace Concept & Strategy for the ECAC Area & Key Enablers Edition 2.0," EUROCONTROL, February 2008.

[6] D. De Smedt and G. Berz, "Study of the Required Time of Arrival Function of Current FMS in an ATM Context," 26th Digital Avionics Systems Conference, Dallas, Texas, 2007.

[7] J. Klooster, A. DelAmo, P. Manzi "Controlled Time of Arrival Flight Trials – Results and Analysis," Eighth USA/Europe Air Traffic Management Research and Development Seminar, Napa, CA, 2009.

[8] J. Klooster, K. Wichman, O. Bleeker, "4D Trajectory and Time-of-Arrival Control to Enable Continuous Descent Arrivals," AIAA Guidance, Navigation and Control Conference and Exhibit, Honolulu, Hawaii, August 2008.

[9] Cassis Project, "CTA/ATC System Integration Studies (CASSIS) II Flight Trials Report," Version 1.0, February 2010.

[10] M. Jackson, "CDA with RTA in a mixed Environment," 28th Digital Avionics Systems Conference, Orlando, FL, October 2009.

[11] J. Scharl, A. Haraldsdottir, J. King, R. Shomber, K. D. Wichman, "A Fast-Time Required Time of Arrival Model for Analysis of 4D Arrival Managment Concepts," AIAA Modeling and Simulation Technologies Conference, Honolulu, Hawaii, 2008.

[12] A. Haraldsdottir, J. Scharl, J. King, E. G. Schoemig, M. E. Berge, "Analysis of Arrival Management Performance with Aircraft Required Time of Arrival Capabilities," 26th International Congress of the Aeronautical Sciences, Anchorage, Alaska, 2008.

[13] "Validation Report of the I4D first flight to support Release 1 - issue02,", SESAR Consortium, Deliverable 9.01.D21-02, June 2012.

[14] J. Klooster, D. De Smedt, "Controlled Time of Arrival Spacing Analysis," Ninth USA/Europe Air Traffic Management Research and Development Seminar, Berlin, Germany, June 2011.

[15] "User manual for the Base of Aircraft Data (BADA) Revision 3.7," EEC Technical/Scientific Report No. 2009-003, July 2003.

[16] M. Jackson, "Sensitivity of Trajectory Prediction in Air Traffic Management and Flight Management Systems," Doctoral Thesis, University of Minnesota, 1997.

[17] "Airbus A320 Flight Crew Operating Manual (FCOM) Quick Reference Handbook (QRH)," Airbus.

[18] "Airbus A330 Flight Crew Operating Manual (FCOM) Quick Reference Handbook (QRH)," Airbus.

[19] "Boeing 737NG Flight Crew Operations Manual (FCOM) Quick Reference Handbook (QRH)," Boeing.

[20] "Boeing 777-300ER Flight Planning and Performance Manual (FPPM)," Boeing.

[21] M. DeJonge, "Time controlled navigation and guidance for 737 aircraft, Technical Note, Smiths Industries," Grand Rapids, MI, November 1988.

[22] D. De Smedt, T. Pütz, "Flight Simulations Using Time Control With Different Levels Of Flight Guidance," Digital Avionics Systems Conference, Orlando, Florida, October 2009.

[23] C. Garcia-Avello, S. Swierstra, "Free Flight, until where… and then?," CEAS 10th European Aerospace Conference on Free Flight, paper 10-1, Amsterdam, The Netherlands, October 1997.

[24] "Getting to grips with fuel economy, Issue III, page 66," Airbus, July 2004.

[25] S. Raynaud, "EUROCAE WG-85 White paper ETAmin-ETAmax, Reference WG85-01," Airbus, July 2011, unpublished.

[26] "Speed and Route Advisor (SARA)," Knowledge and Development Center Mainport Schiphol, http://www.kdc-mainport.nl.

AUTHOR BIOGRAPHY

David De Smedt obtained a Masters degree in Science of Civil Engineering at the Vrije Universiteit Brussel in 1997. He holds a current Airline Transport Pilot License (ATPL) with Airbus A320 Type Rating and has 2500 hours of airline pilot experience, operating A320 aircraft for Sabena and DutchBird. He currently works as a Senior Navigation Expert for EUROCONTROL, Brussels. His areas of work are 4D-Trajectory Based Operations, Performance Based Navigation and Avionics.

Jesper Bronsvoort is an Aerospace Engineer at Airservices Australia, Melbourne. He works on several initiatives involved in the transition to Trajectory Based Operations in Australia. He holds a BSc degree (2006) and an MSc degree (2011) in aerospace engineering, both from Delft University of Technology, The Netherlands. Currently he is doing his PhD at Universidad Politechnica de Madrid, supported by Airservices and Boeing Research & Technology Europe.

Greg McDonald is an Air Traffic Controller with in excess of 30 years experience in all facets of the craft. Since 1998 has been involved in the Australian ATM Strategic Plan and implementing efficiencies for airlines including AUSOTS flex tracks. His work managing the Tailored Arrivals program for Australia has lead to his interest in improving ground based trajectory prediction to efficiently manage the increasing air traffic. He is currently researching how currently deployed equipment (FANS) can be employed to improve ground prediction and processing.